APPENDIX D

COMPUTATION OF DISCHARGE RATING CURVES FOR OUTLET WORKS
(Illustrative Example)

D-1. Introduction. The following simplified example is presented to illustrate some of the procedures and guidance given in Chapter 2 and paragraph 4-16 for developing rating curves for outlet works. The procedures are applicable with or without the aid of a programmed computer. A number of comments applying to any conduit discharge computations are included.

D-2. Multiple Conduits. For an outlet works composed of several conduits operating in parallel, the total flow must be proportioned among the conduits before the head-discharge relation can be determined. The division of flow depends upon the nature of the conduit layout; that is, when all the conduits are identical in size, length, shape, and invert elevation and have uniform flow conditions at entrances and exits, the flow will be distributed equally. When the outlet works contain conduits of several sizes which have the same entrance control, the distribution of flow in the conduits is determined by assuming pool elevations and calculating individual conduit discharges. When the conduits are variable in size or the invert elevations are not identical and the discharge control does not occur at the entrance, trial distributions of assumed total discharges must be made; and pool elevations, corresponding to the trial discharges, must be determined for each conduit. The correct flow distribution will be determined when the computed pool elevations are identical for all of the conduits.

D-3. Example Structure. The outlet works selected for this sample computation have two 11- by 22-ft gate passages, a transition section, a 22-ft circular conduit, and a parabolic drop into the stilling basin. A section along the center line of the conduit is shown in plate D-1. Rating curves should be computed for both $k = 0.002$ ft (capacity) and smooth pipe (velocity) conditions for full flow and $k = 0.007$ ft and 0.002 ft, respectively, for partly full flow. This example is limited to the capacity curve computations.

D-4. Computer Programs. A number of computer programs applicable to developing rating curves have been developed and these are available on the computer-aided design system CORPS. The applicable CORPS program name(s) will be noted throughout this example problem. It is recommended that the designer periodically check the list of available programs in CORPS to determine if additional programs have been added to the system.

He should also check with the WES Engineer Computer Program Library to see if programs are available outside of the CORPS system.

D-5. <u>Discharge Controls.</u> The computation of flow through a conduit usually involves consideration of several conditions of flow. During diversion when the upper pool is at low stages or at lower partial gate openings at any stage, open-channel flow may occur in the conduit. As the reservoir level is raised or the gate opening is increased, the depth of flow in the conduit increases until the conduit flows full. Determinations are needed of whether there is inlet control, outlet control, critical depth control, or gate control and when the control shifts from one type to another. Definition of the discharge curves requires open-channel, pressure flow, and gate discharge computations. The open-channel flow computations probably will require flow profiles to evaluate energy losses and establish the limits of the open-channel flow ranges for both diversion and gated flow conditions.

D-6. <u>Hydraulic Characteristic Curves.</u> Prior to determining conditions of open-channel flow and type of control and computing the rating curves, the following hydraulic characteristic curves should be prepared:

a. Tailwater stage-discharge curves for several conditions of any anticipated downstream channel degradation or aggradation (see para 1-10b(4)(a)).

b. Conduit cross-sectional areas of flow in square feet plotted as abscissas against flow depths in feet plotted as ordinates. (CORPS H6002, H2040, H2041, H2042,[o] or King's Handbook (item D-4) Table 7-4.)

c. Conduit hydraulic radii of flow section in feet as abscissas against flow depths in feet as ordinates. (CORPS H6002, H2040, H2041, H2042,[o] or King's Handbook (item D-4) Tables 7-1 or 7-5.)

d. Conduit discharges in cubic feet per second as abscissas against the corresponding critical depths in feet as ordinates. (CORPS H6140, H6141,[o] or King's Handbook (item D-4) Tables 8-4, 8-5, 8-9, or 8-10.)

e. Conduit discharges in cubic feet per second as abscissas against the corresponding normal depths in feet as ordinates. (CORPS H6113 to H6118.[o])

If manual computations are used, the conduit characteristic curves should be plotted to a sufficiently large scale so that areas may be read to the nearest square foot and hydraulic radius to the nearest 0.01 ft. Approximate characteristic curves for the 22-ft circular conduit are shown in plate D-1. The discharge curves indicate that when open-channel flow occurs in the conduits, normal depth is greater than critical depth for each discharge, and a practical maximum depth is about 18 ft. Therefore, critical depth discharge control will occur at the outlet (sta 10+70). If the tailwater causes the flow to be at greater than critical depth at the outlet, there will then be less discharge for a given pool elevation. Backwater computations are required to determine the water-surface elevation at the intake. Also, they may be required at selected discharges extending over the full range of open-channel flow to determine whether and how much the tailwater influences open-channel discharge in the conduits.

D-7. Discharge Curves. The computed discharge curves (capacity) for the 22-ft circular conduit are shown in plate D-2. Computations of the various parts of the curves for the different flow conditions are explained in the following paragraphs. The transitions from partly full to full or pressure flow and vice versa cannot be computed with present theory and must be estimated by judgment. The shaded areas on the curve represent these regions in which head-discharge relations may be unstable, subject to a rising or falling pool. On a rising pool (with gates fully open) it was assumed that open-channel flow conditions existed until the flow depth in the intake was equal to approximately 90 percent of the conduit diameter, after which flow conditions shifted rapidly to less efficient, full conduit flow at a lower discharge. On a falling pool it was assumed that pressure flow existed until the pool elevation dropped a few feet below the shift elevation for a rising pool, in this case to the intake crown level. Actual prototype behavior of a conduit with similar geometry would be helpful but such information is generally lacking. Model studies may be helpful in some cases where operation in the unstable range is necessary.

D-8. Open-Channel Discharge. Flow control will occur at sta 10+70 for all open-channel discharges (without gate control). In this case, the head-discharge relation for open-channel flow is determined from the curve of discharge at critical depth (see para D-6d above and plate D-1), backwater curve computations to sta 2+00, and intake losses upstream of sta 2+00. Typical computations are summarized in table D-1 and plotted as curve A in plate D-2. Backwater curve computations are described in paragraphs D-11 and D-12.

D-9. Pressure Flow. Discharge for a conduit flowing full is determined by equations and computations for conduit losses and discharges given in table D-2 and plotted as curve B in plate D-2.

Table D-1

Summary of Example Computations for Head-Discharge Curve
Open-Channel Flow, Critical Depth Control at Outlet
(Capacity Flow)

D = 22 ft; S = 0.00115; k = 0.007 ft; L = 870 ft; $\nu = 1.21 \times 10^{-5}$ ft^2/sec at 60°F; $K_e = 0.38$†; $K_v = 1.00$

See plate D-1 for y_c (critical depth), y_o (normal depth), R (hydraulic radius) and Area

See table D-3 for example manual computations of water-surface profile, or use CORPS H6208.^{o}

For a given Q:

Pool elevation = conduit invert elevation (1229) + y + $(K_e + K_v) \frac{V^2}{2g}$, all segments at sta 2+00.

Sta 10+70 Q cfs	Sta 10+70 y_c ft	Sta 10+70 y_o ft	0.99 y_o Sta ft	Sta 2+00 y* ft	Sta 2+00 V fps	Sta 2+00 $V^2/2g$ ft	1.38 $V^2/2g$ ft	Pool El ft msl
250	2.98	3.67	2+50*	3.67	6.00	0.56	0.77	1,233.4
500	4.24	5.21	††	5.11	7.45	0.86	1.19	1,235.3
1,000	6.04	7.49	††	7.26	9.14	1.30	1.79	1,238.0
2,000	8.65	11.10	††	10.41	11.29	1.98	2.73	1,242.1
3,000	10.69	14.45	††	12.96	12.89	2.58	3.56	1,245.5
3,900	12.26	18.05	††	15.01	14.11	3.09	4.26	1,248.3

Conduit flows full at 3940 cfs

* Values obtained with CORPS H6208.^{o}

† Coefficient for open-channel flow intake loss upstream from sta 2+00 assumed to be 50% larger than pressure flow coefficient of 0.25 from plate C-32.

†† $0.99y_o$ would occur upstream from sta 2+00 if conduit section was extended upstream.

Table D-2

Example Head-Discharge Computations for Conduit Flowing Full Pressure Flow (Capacity)

$D = 22$ ft $A = 380\ ft^2$ $T = 60°F$ $\nu = 1.21 \times 10^{-5}\ ft^2/sec$ $L = 870$ ft

k = 0.0020 ft (for capacity) $\frac{D}{k} = 11{,}000$ $\mathbb{R} = \frac{VD}{\nu}$ $\mathbb{F} = \frac{V}{\sqrt{gD}}$ $K_f = f\frac{L}{D}$

For a given discharge:

Pool elevation = Exit portal invert elevation (1228.0) + y_p + H

where $H = K\frac{V^2}{2g}$ and $K = K_e + K_f + K_v$

Q cfs	V fps	$V^2/2g$ ft	$\mathbb{F}$†	y_p/D††	y_p ft	$\mathbb{R}/10^7$	f‡	K_f	K_e‡‡	K_v	K	H ft	Pool Elevation ft msl
5,000	13.15	2.7	0.5	1.00	22.0	2.37	0.0118	0.47	0.25	1.00	1.72	4.6	1,254.6
10,000	26.3	10.7	1.0	0.82	18.0	4.74	0.0118	0.47	0.25	1.00	1.72	18.4	1,264.4
15,000	39.5	24.2	1.5	0.72	15.8	7.12	0.0118	0.47	0.25	1.00	1.72	41.6	1,285.4
20,000	52.6	43.0	2.0	0.67	14.7	9.48	0.0118	0.47	0.25	1.00	1.72	74.0	1,316.7
25,000	65.8	67.2	2.5	0.63	13.9	11.9	0.0118	0.47	0.25	1.00	1.72	115.6	1,357.5
30,000	78.9	96.7	3.0	0.61	13.4	14.2	0.0118	0.47	0.25	1.00	1.72	116.3	1,407.7

† Froude number.

†† Pressure gradient at exit portal from plate C-3 (extrapolated for $\mathbb{F}$ = 0.5).

‡ Darcy-Weisbach resistance coefficient from plate C-4. (In computing conduit discharge and flow velocity for energy dissipator, use smooth pipe curve.)

‡‡ Intake loss coefficient for double intake (similar to Fort Randall prototype) from plate C-32.

D-10. Gate-Controlled Discharge. The head-discharge relation for partial gate openings with free-surface flow downstream (see para 4-16 and CORPS H3201°) is modified to include intake losses upstream of the gates. Typical computations are given in table D-3 and plotted as curve C in plate D-2. If pressure flow occurs downstream from the gates, the head-discharge relation can be computed as in paragraph D-9 above with an added loss coefficient for the partly open gates. This loss coefficient can be determined from the gate flow contraction coefficient (plate C-39), an abrupt expansion loss coefficient (plate C-8), and a conversion to the appropriate reference section (as noted in para 2-13(a)). Local pressures just downstream from the gate should then be checked by subtracting the contracted jet velocity head from the pressure grade line just upstream from the gate. If the local pressure is subatmospheric, air will be drawn through the vents. (See para 3-17 in main text.) This will reduce the effective head through the gate and produce aerated flow in the conduit downstream from the gate, both factors severely complicating calculation of a head-discharge relation in this flow condition. Slug flow also may occur in this range of unstable flow (see para D-13 below).

D-11. Profile Analysis. The open-channel flow computations generally involve flow profile calculations. A qualitative profile analysis should precede computations in order to predict the general shape of the possible flow profiles that may occur in a conduit system. See paragraph 2-3, plate C-1, and Chow (item D-2, Chapter 9) for more information and procedures. Typical profiles in an outlet works conduit might include:

a. M2 upstream and S2 downstream from a point of critical depth control.

b. M1, M2, C1, or S1 upstream from conduit outlet, depending on stilling basin apron slope and tailwater elevation.

c. H3, M3, C3, or S3 downstream from a partly open gate.

Rapidly varied profiles may occur in the intake and transition, at the outlet, at any hydraulic jump, at changes in cross section and alignment, and past obstacles. Except for a few relatively simple boundary configurations, these conditions are very difficult to compute accurately and will require experimental evaluation. In this example M2 curves occur upstream of the outlet for low flows and M3 curves occur downstream of the gate at partial openings.

D-12. Flow Profiles Through Conduits. Most of any needed computations can be done with CORPS H6208 and H6209° for straight, uniform-section

Table D-3

Head-Discharge Computations for Partly Open Gates
Open-Channel Flow Downstream

$Q = B\ C_c\ G_o\ P\ \sqrt{2g(H-E-C_cG_o)}$

B = gate passage width = 11 ft
P = number of gate passages = 2
g = gravitational acceleration = 32.2 ft/sec^2
E = gate passage invert elevation = 1229 ft msl
C_c = contraction coefficient (plate C-39)
G_o = gate opening, ft
H = energy grade line elevation at gate, ft msl

$Q = 22\ C_cG_o\ \sqrt{64.4\ (H-1229-C_cG_o)}$

$$\text{Pool El} = H + K_e \frac{V_p^2}{2g}$$

K_e = Intake loss coefficient = 0.16 (plate C-32)
(short, streamlined entrance upstream from gate assumed similar to sluice intake, or about half of full loss for this type of tunnel intake).

V_p = average velocity in gate passage upstream from gate = Q/(2x11x22) = Q/484 fps

Gate Opening G_o, ft	Contr Coeff C_c	EGL El H, msl	Disch Q cfs	V_p fps	$K_e\ V_p^2/2g$ ft	Pool El $H+K_e\ V_p^2/2g$
5.50	0.734	1,250.00	2,935	6.07	0.09	1,250.09
		1,260.00	3,701	7.65	0.15	1,260.15
		1,280.00	4,884	10.10	0.25	1,280.25
		1,300.00	5,835	12.06	0.36	1,300.36
		1,320.00	6,649	13.74	0.47	1,320.49
		1,340.00	7,374	15.24	0.58	1,340.58
		1,360.00	8,034	16.60	0.68	1,360.68
		1,380.00	8,644	17.86	0.79	1,380.79
11.00	0.752	1,250.00	5,215	10.77	0.29	1,250.29
		1,260.00	6,969	14.40	0.51	1,260.51
		1,280.00	9,555	19.74	0.97	1,280.97
		1,300.00	11,578	23.92	1.42	1,301.42
		1,320.00	13,296	27.47	1.88	1,321.88
		1,340.00	14,816	30.61	2.33	1,342.33
		1,360.00	16,194	33.46	2.78	1,362.78
		1,380.00	17,464	36.08	3.23	1,383.23
16.50	0.793	1,250.00	6,503	13.44	0.45	1,250.45
		1,260.00	9,782	20.21	1.01	1,261.01
		1,280.00	14,229	29.40	2.15	1,282.15
		1,300.00	17,585	36.33	3.28	1,303.28
		1,320.00	20,397	42.14	4.41	1,324.41
		1,340.00	22,865	47.24	5.54	1,345.54
		1,360.00	25,091	51.84	6.68	1,366.68
		1,380.00	27,136	56.07	7.81	1,387.81

conduits flowing partly full. Although the Manning n coefficient has been extensively used for free-surface flow, use of the Darcy f or Chezy C relates losses to the Reynolds number of the flow as well as to a physical estimate of the equivalent boundary surface roughness k. The relations between the coefficients C, f, and n can be expressed as $C/1.486 = 10.8/f^{1/2} = R^{1/6}/n$, where R is the hydraulic radius of the flow boundary. The basic theory is given in Chapter 2 of the main text. Application of the theory to free-surface flow is covered in paragraphs 7 and 8 of EM 1110-2-1601.[h] A sample computation using k and C in a nonprismatic channel is given in plate 9 of EM 1110-2-1601.[h] Equivalent roughness heights k of 0.007 ft for capacity and 0.002 ft for velocities are recommended for concrete conduits in accordance with the guidance given in EM 1110-2-1601.[h] Although it is sometimes assumed that free-surface flow is hydraulically rough flow in large concrete conduits, the example given in table D-4 for a surface profile upstream from the outlet is applicable to smooth surface and transition zone flows. An enlarged portion of the open-channel flow resistance coefficients diagram from HDC 631[n] (similar to Moody diagram in plate C-4) is given in plate D-3 for computational convenience.

D-13. <u>Slug Flow.</u> Slug flow occurs when the discharge and energy level are almost sufficient to cause the conduit to flow full. It will occur in any conduit that is operated at a given pool level with discharges that will produce either full or partly full flow conditions. It is most often encountered in long, small diameter conduits. In this flow transition zone, between partly full and full flow, large air bubbles (the slugs) are trapped by the flow and are separated by sections of full flow in the conduit. Although these slugs can move in an upstream direction in conduits with steep slopes, or low velocities (see plate D-4 and item D-3), they most commonly move downstream in an outlet conduit. Neither the air bubbles nor the water sections will cause any impact on the conduit proper; but they may impact on appurtenances at the ends of a conduit. Should the slugs move upstream they can cause adverse gate vibrations and possible air vent damages, or if the conduit does not have gates, trashrack vibration problems. In the more common case with the slugs moving downstream, the impact is wave action through the energy dissipator and the downstream channel. Because these impacts are usually very adverse, the designer should try to obtain a design such that the range of troublesome discharges is sufficiently narrow to permit it to be quickly passed through without changing the downstream water levels and/or velocities too rapidly, or a design such that slug flow conditions will occur only under unusual and infrequent operating conditions of short duration.

D-14. <u>Slug Flow Limits.</u> The following procedure can be used to determine the lower and upper discharge limits for a given pool level within which slug flow can be expected to occur. Reasonably good correlation was obtained between the calculated limits and those obtained from the Warm Springs Outlet Works model study (item D-1). The lower discharge limit of slug flow for any pool level is approximately equal to the minimum, part-gate discharge which will cause the conduit to flow full. The conduit is determined to flow full if a water-surface profile computation initiated at the vena contracta immediately downstream of the gate indicates that the depth will increase to about 80 to 85 percent of the conduit height before exiting the downstream portal. Entrained air is assumed to bulk the flow 15 to 20 percent and thereby effect full conduit flow with the above-computed depths of nonaerated water. The upper discharge limit for a given pool level is approximately equal to the discharge for which the downstream momentum at the vena contracta with partly full flow is equal to the upstream momentum that would occur at the gates with the same discharge if the complete conduit were flowing full. The sketch in plate D-4 defines these two conditions for computation of this discharge. For a given pool level, assume a gate opening G_o and compute the free flow discharge Q and the momentum at the vena contracta (condition 1):

$$M_1 = A_1\bar{y}_1 + \frac{QV_1}{g} \qquad \text{(D-1)}$$

where

A = cross-sectional area of flow

$\bar{y}$ = distance from hydraulic grade line (free surface for open-channel condition) to centroid of flow area

V = average velocity through A

Then, assuming the conduit to flow full at the same Q, compute the elevation of the piezometric grade line (PGL) at the gate (starting from the downstream portal) and the momentum of the full-conduit flow at the gate (condition 2):

$$M_2 = A_2\bar{y}_2 + \frac{QV_2}{g} \qquad \text{(D-2)}$$

Adjust the assumption of G_o as necessary to give a value of Q that will result in equal values of M and M_2. Then make similar computations for other pool levels in the range of interest. Increasing the conduit slope will raise both limits and will narrow the band of

Table D-4. Example Computation of Flow Profile at 3000 cfs using k and Chezy C

Station ft	Invert El ft msl	W.S. El ft msl	y ft	A ft^2	V fps	$\left\lvert \frac{V_2 - V_1}{\frac{V_2 + V_1}{2}} \right\rvert$ *	$h_v = \frac{V^2}{2g}$ ft	Trial EGL El ft msl
10+70	1228.00	1238.69	10.69	183.25	16.37	--	4.17	1242.86
10+65	1228.01	1239.15	11.14	193.15	15.53	0.053	3.75	1242.90
10+50	1228.02	1239.32	11.30	196.67	15.25	0.018	3.61	1242.93
10+00	1228.08	1239.93	11.85	208.75	14.37	0.059	3.21	1243.14
		1239.78	11.70	205.46	14.60	0.044	3.31	1243.09
		1239.58	11.50	201.06	14.92	0.022	3.46	1243.04
9+00	1228.20	1239.90	11.70	205.46	14.60	0.022	3.31	1243.21
8+00	1228.31	1240.21	11.90	209.84	14.30	0.021	3.18	1243.39
		1240.26	11.95	210.94	14.22	0.026	3.14	1243.40
7+00	1228.43	1240.63	12.20	216.41	13.86	0.026	2.98	1243.62
6+00	1228.54	1241.01	12.47	222.31	13.50	0.027	2.83	1243.84
5+00	1228.66	1241.38	12.72	227.75	13.17	0.025	2.70	1244.08
		1241.36	12.70	227.32	13.20	0.023	2.71	1244.07
		1241.31	12.65	226.23	13.26	0.018	2.73	1244.04
4+00	1228.77	1241.57	12.80	229.49	13.07	0.014	2.66	1244.23
		1241.62	12.85	230.57	13.01	0.019	2.63	1244.25
		1241.47	12.70	227.32	13.20	0.005	2.71	1244.18
3+00	1228.89	1241.64	12.75	228.40	13.14	0.005	2.68	1244.32
2+00	1229.00	1241.80	12.80	229.49	13.07	0.005	2.66	1244.46
		1241.83	12.83	230.14	13.04	0.008	2.64	1244.47
		1241.88	12.88	231.22	12.97	0.013	2.62	1244.50

Note: $Q = 3000$ cfs
$k = 0.007$ ft (capacity)
$S = 0.00115$
$\alpha = 1.000$
$D = 22.00$ ft
$\nu = 0.0000121\ ft^2/sec$ at 60° F.
* If not ≤ 0.10, reduce distance between stations.
** If in fully rough flow, $C = 32.6 \log_{10} (12.1\ R/k)$.

R ft	R/k	$\mathbb{R} = \frac{4RV}{\nu}$	C**	$S_f = \frac{V^2}{C^2R}$	S_f avg	L	h_f	Check EGL El ft msl	Y from CORPS H6208 ft
5.40	771.37	2.92×10^7	129.54	0.002959				1242.86	10.69
					0.002769	5	0.01	1242.87	
5.54	791	2.84×10^7	129.9	0.00258					11.14
					0.00252	5	0.01	1242.88	
5.59	798.6	2.82×10^7	130.0	0.00246					11.27
					0.00228	50	0.114	1242.99	
5.76	822.86	2.74×10^7	130.45	0.00211	0.00233		0.116	1243.00	
5.71	816.24	2.76×10^7	130.34	0.00220	0.00239		0.12	1243.00	
5.66	808.57	2.79×10^7	130.19	0.00232					11.62
					0.00226	100	0.226	1243.23	
5.71	816.24	2.76×10^7	130.34	0.00220					11.97
					0.00214	100	0.21	1243.44	
5.77	824.48	2.73×10^7	130.48	0.00208	0.00202		0.20	1243.43	
5.79	826.51	2.72×10^7	130.52	0.00205					12.20
					0.001985	100	0.198	1243.63	
5.86	836.43	2.68×10^7	130.69	0.00192					12.38
					0.00186	100	0.186	1243.82	
5.93	846.75	2.65×10^7	130.86	0.00179					12.53
					0.00174	100	0.174	1243.99	
5.99	855.95	2.61×10^7	131.01	0.00169	0.00174	100	0.174	1243.99	
5.99	855.71	2.61×10^7	131.01	0.00169	0.00175		0.175	1244.00	
5.97	853.41	2.62×10^7	130.97	0.00172					12.66
					0.00169	100	0.169	1244.17	
6.01	858.81	2.60×10^7	131.06	0.00166	0.00168		0.168	1244.17	
6.02	860.59	2.59×10^7	131.09	0.00164	0.00171		0.171	1244.17	
5.99	855.22	2.61×10^7	131.00	0.00170					12.77
					0.00169	100	0.169	1244.34	
6.00	857.02	2.61×10^7	131.031	0.00168					12.87
					0.00167	100	0.167	1244.51	
6.01	858.81	2.60×10^7	131.06	0.00166	0.00166		0.166	1244.51	
6.02	859.88	2.60×10^7	131.08	0.00164	0.00165		0.165	1244.50	
6.03	861.64	2.58×10^7	131.11	0.00162					12.96

discharge within which slug flow will occur, while reducing the slope will produce the opposite effect. Changing the conduit size will primarily affect the lower limit. Increasing the size will raise the lower limit while decreasing the size will lower the lower limit. In most cases a change in both slope and size will be necessary to maintain discharge capacity and effect the desired change in band width or shift of the limits of slug flow. As the normal change combinations have opposite effects, each case will be unique and generalized guidance cannot be given.

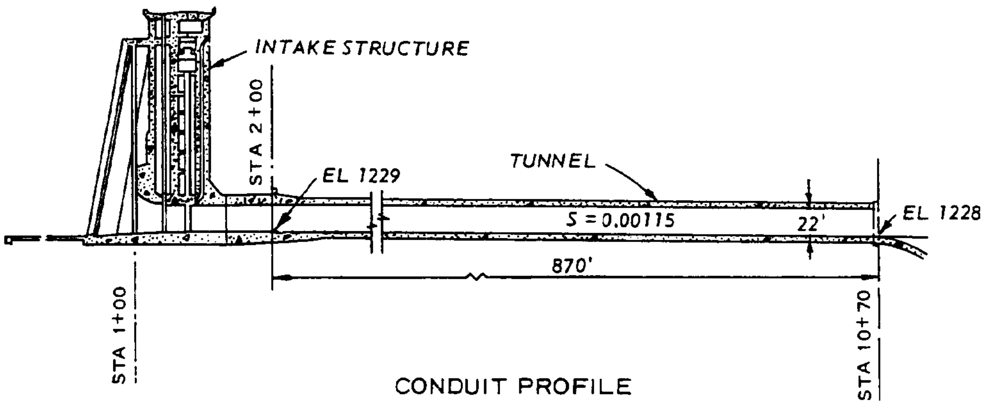
D-15. References.

D-1. Ables, J. H., Jr., and Pickering, G. A. 1973 (Feb). "Outlet Works, Warm Springs Dam, Dry Creek, Russian River Basin, Sonoma County, California; Hydraulic Model Investigation," Technical Report H-73-3, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

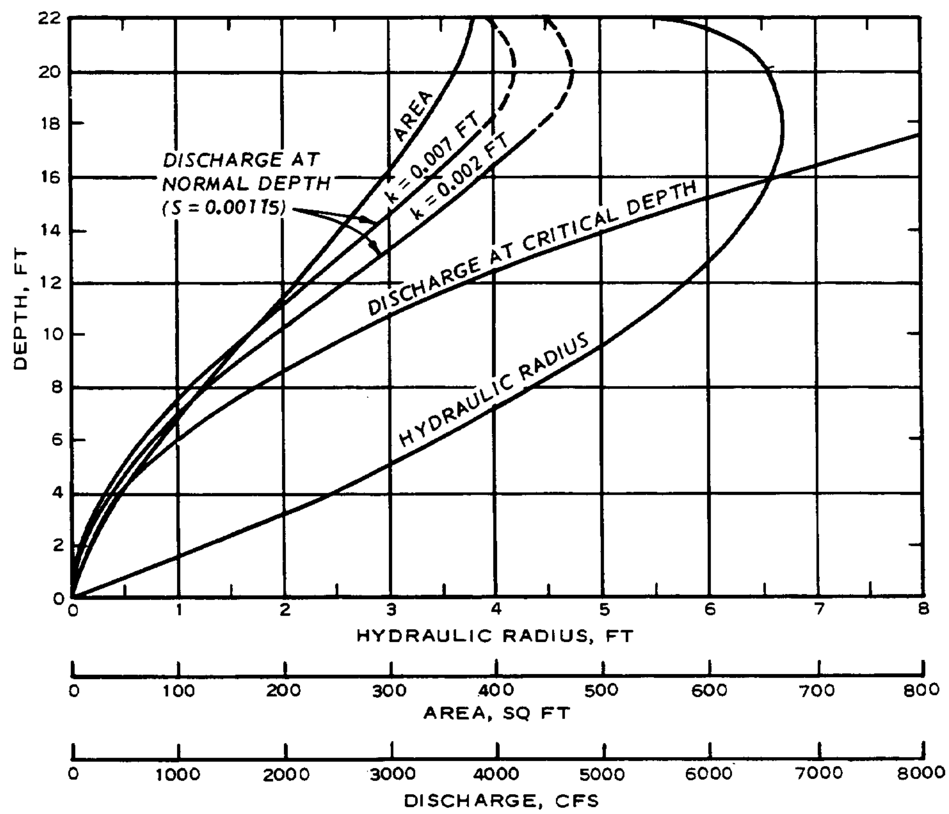
D-2. Chow, V. T. 1959. Open-Channel Hydraulics, McGraw-Hill, New York.

D-3. Falvey, H. T. "Air-Water Flow in Hydraulic Structures" (in preparation), Engineering Monograph 41, U. S. Bureau of Reclamation, Denver, Colo.

D-4. King, H. W., and Brater, E. F. 1963. Handbook of Hydraulics for the Solution of Hydrostatic and Fluid-Flow Problems, 5th ed., McGraw-Hill, New York.

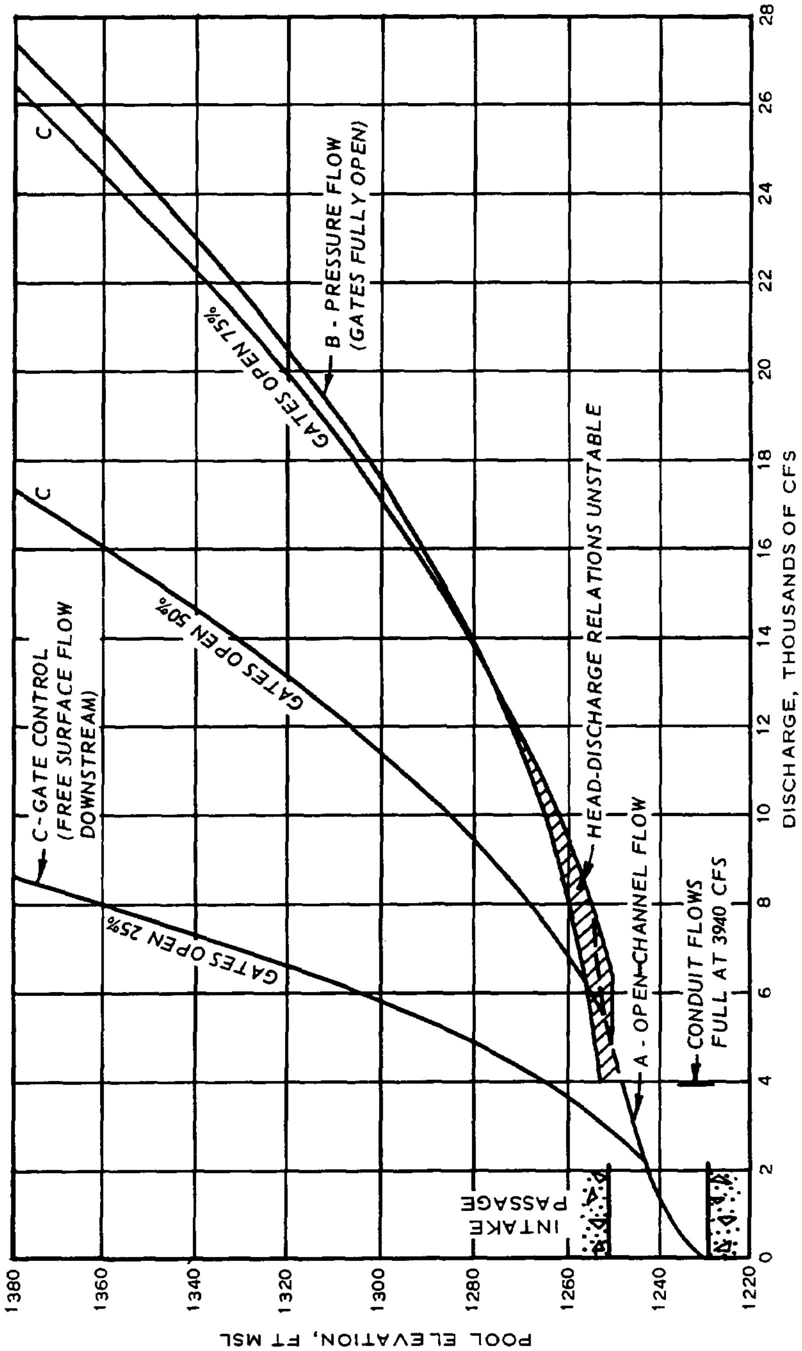


CONDUIT PROFILE



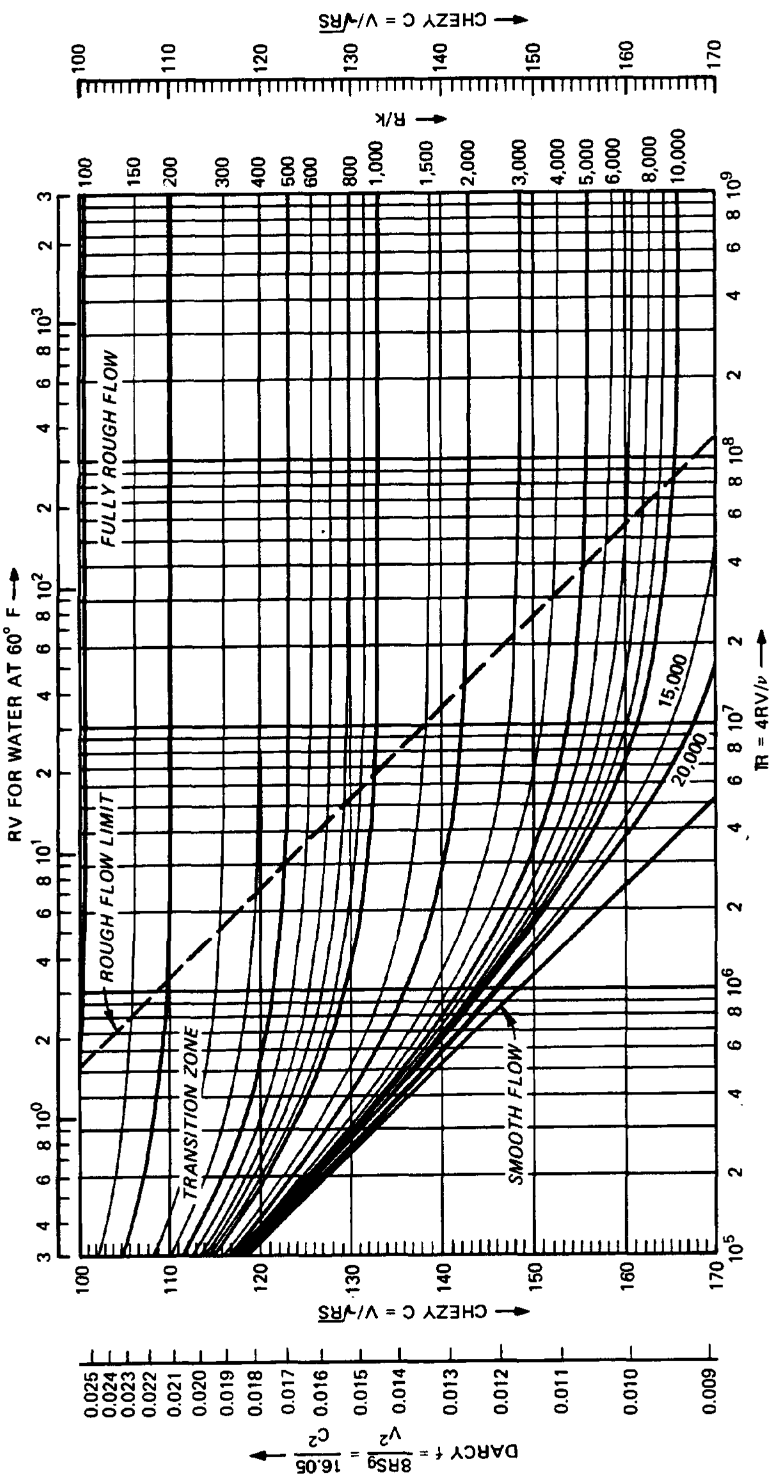
HYDRAULIC CHARACTERISTIC CURVES
FOR 22-FT CIRCULAR CONDUIT

ILLUSTRATIVE EXAMPLE
OUTLET DISCHARGE DETERMINATION



NOTE: SEE TABLES D-1, D-2, AND D-3
FOR ASSUMPTIONS AND COMPUTATIONS.

EXAMPLE
DISCHARGE CURVES (CAPACITY)
22-FT CIRCULAR CONDUIT



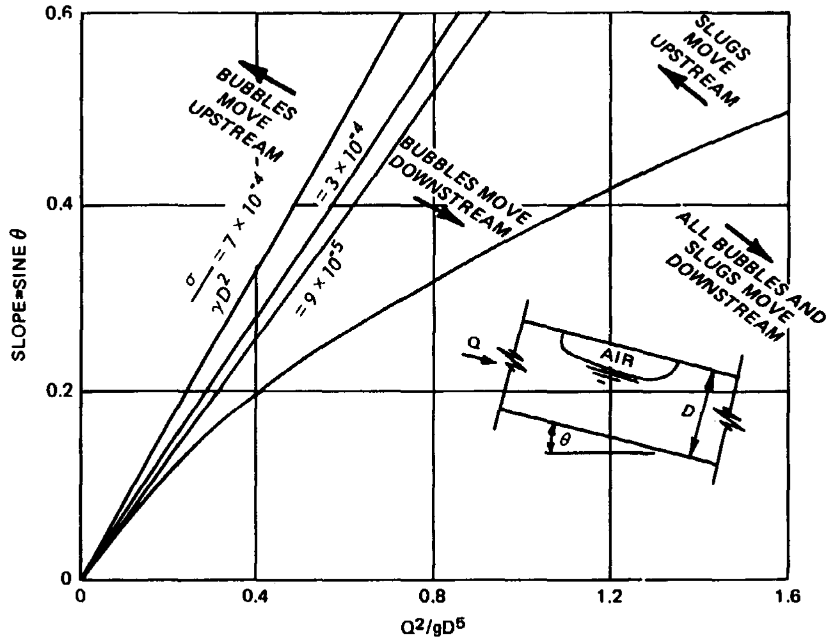
GENERAL EQUATION:
$C = -32.6 \log_{10} (C/5.2ℝ + k/12.2R)$

ROUGH FLOW LIMIT:
$ℝ/C = 50\ R/k$

NOTE: R = HYDRAULIC RADIUS, FT
g = ACCELERATION OF GRAVITY, FT/SEC^2
ν = 0.93×10^{-5} AT 80°F; 1.21×10^{-5} AT 60°F; 1.16×10^{-5} AT 40°F — KINEMATIC VISCOSITY FT^2/SEC
k = EFFECTIVE ROUGHNESS HEIGHT, FT
V = VELOCITY, FT/SEC
S = ENERGY GRADIENT SLOPE
ℝ = REYNOLDS NUMBER

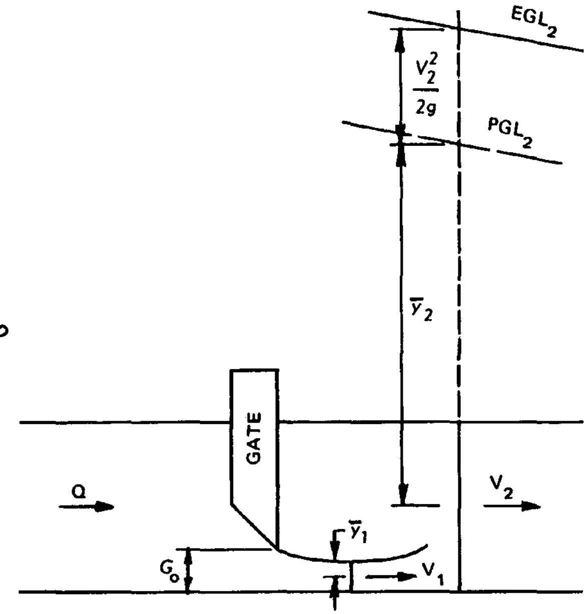
OPEN-CHANNEL FLOW
RESISTANCE COEFFICIENTS

FROM HDC 631



INTERFACIAL SURFACE TENSION		SPECIFIC WEIGHT OF FLUID	
°F	σ, LB/FT	°F	γ, LB/FT³
50	0.00508	50	62.4
60	0.00503	60	62.4
70	0.00497	70	62.3

BUBBLE AND SLUG MOVEMENT IN PIPELINES



DEFINITION SKETCH FOR COMPUTATION OF UPPER DISCHARGE LIMIT FOR SLUG FLOW

(From USBR, item D-3)

SLUG FLOW